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中国科学院高能物理研究所 Institute of High Energy Physics Chinese Academy of Sciences

Laser-Wakefield-Accelerator-Driven MeV Ultrafast Electron Diffraction Source

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Joint Team on Laser Acceleration Applications Research

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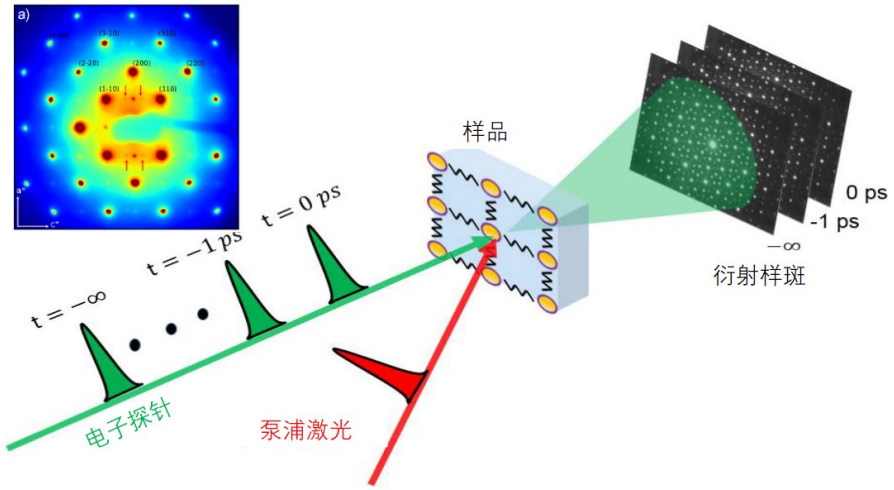
Content

- Ultrafast Electron Diffraction（UED）and Laser Wakefield Accelerator（LWFA）
- LWFA MeV UED platform
- Related studies carried out on the platform
- Summary

Ultrafast Electron Diffraction（UED）

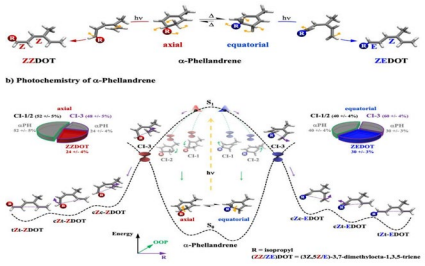
A key tool for probing the microscopic structure of matter

- **Wave–particle duality, picometer-scale matter-wave wavelengths and ultrahigh spatial resolution.**
- **Ultrashort bunch length enables high temporal resolution. A powerful tool for ultrafast structural dynamics studies.**

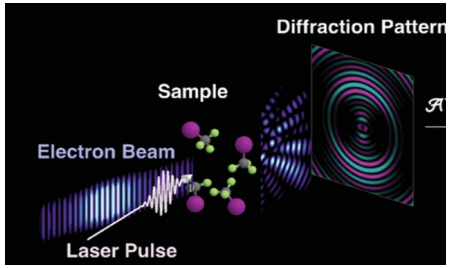


Representative International Achievements in MeV UED

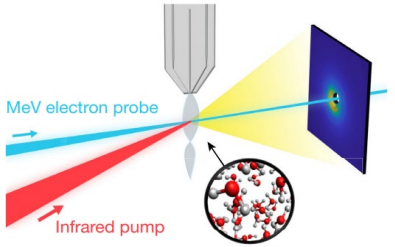
2021, Science
Ultrafast photochemical process imaging



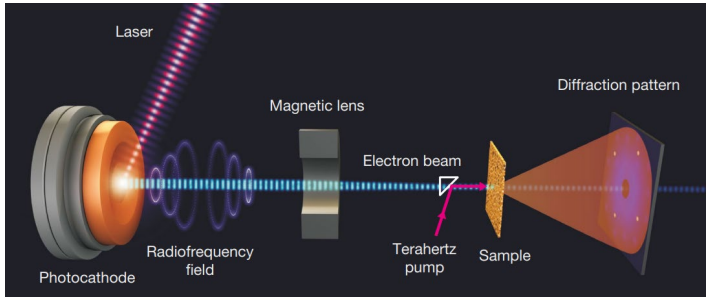
2018, Science
Photodissociation Dynamics of CF_3I



2021, Nature
Hydrogen-Bond Strengthening in Liquid Water



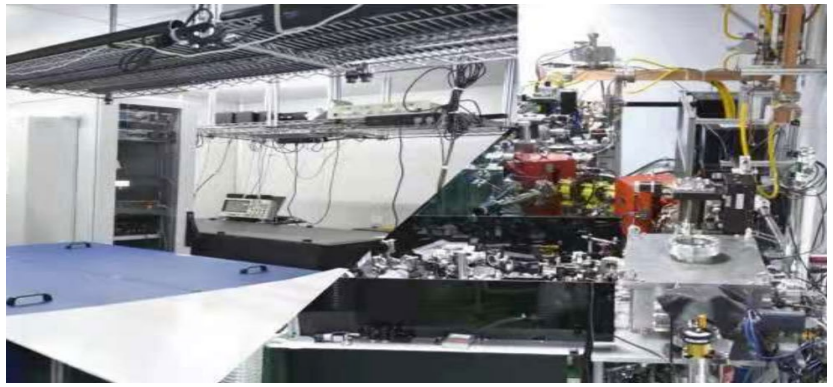
2019, Nature
Research on the Symmetry of Weyl Semiconductors



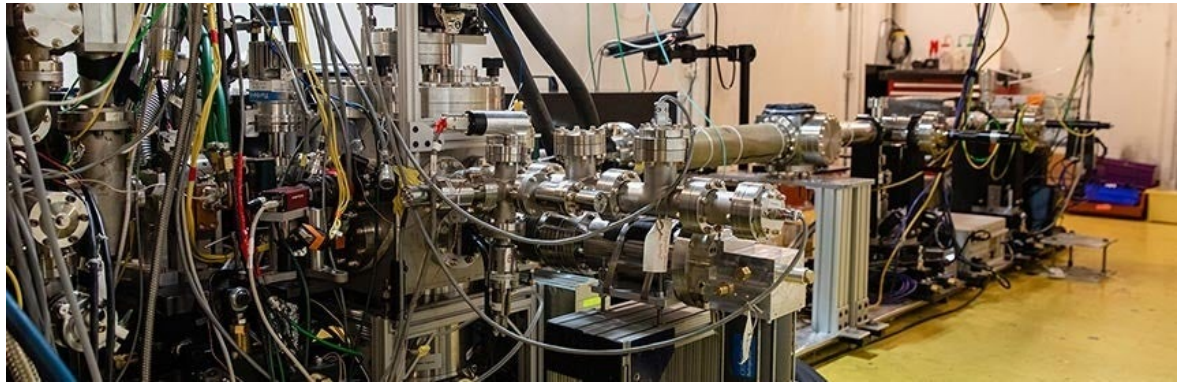
Conventional MeV-UED source

Typical UED facility

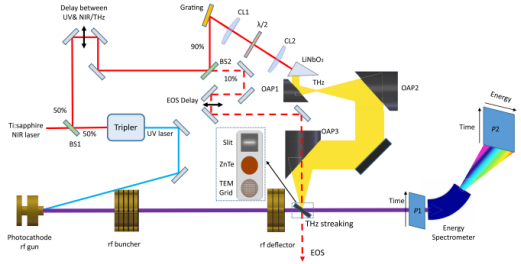
SJTU Ultrafast Electron Diffraction Facility



SLAC MeV Ultrafast Electron Diffraction Facility

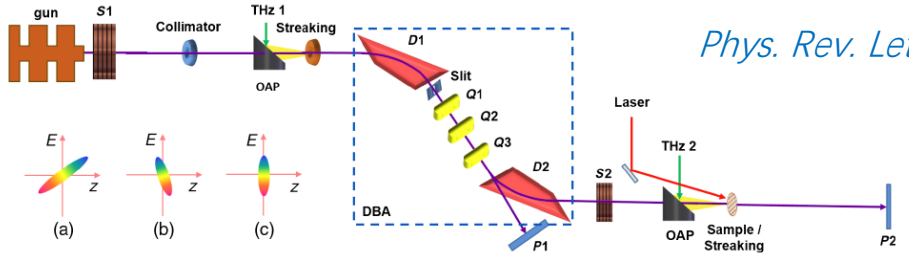


- **Buncher——bunch compression**

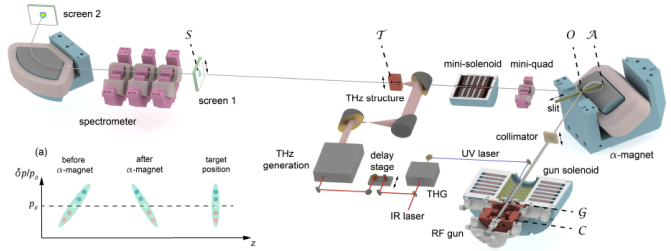


Phys. Rev. X 8, 021061 (2018).

- **Isochronous beam transport structure ——Timing Jitter Reduction**

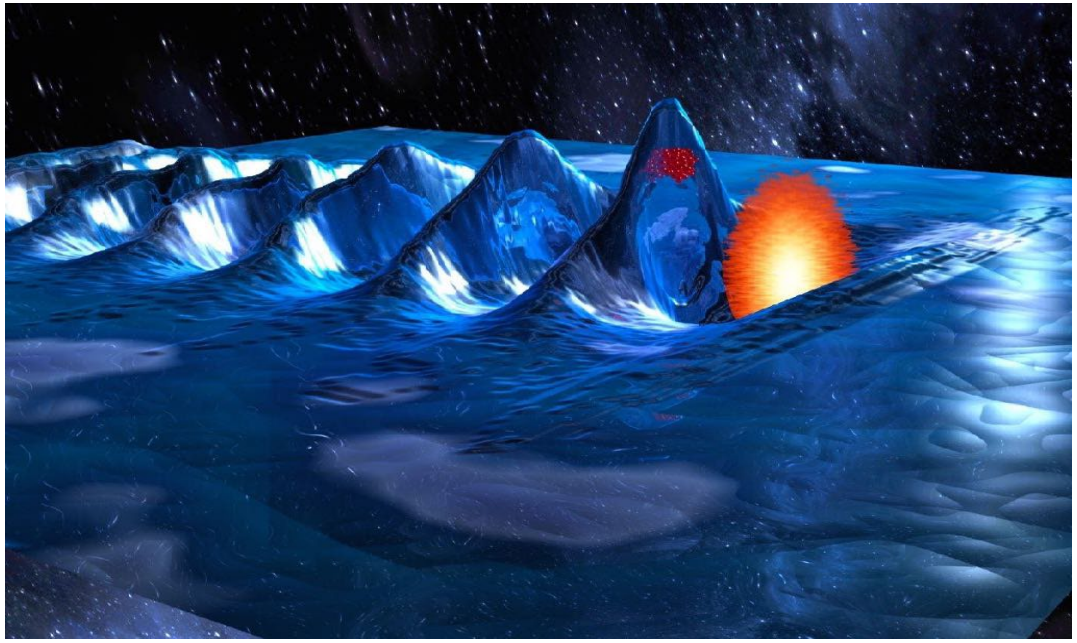


Phys. Rev. Lett, 2020, 124(13).



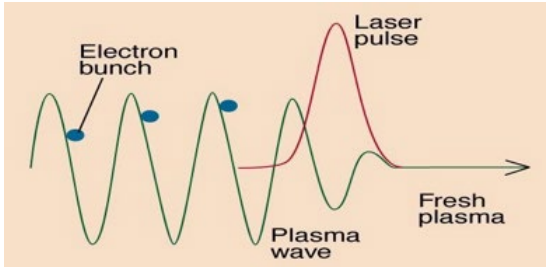
arXiv:2508.03946

Laser Wakefield Accelerator（LWFA）





- **Ultrahigh acceleration gradient (1–100 GV/m)**
- **Ultrasmall accelerating structure (10–100 μm)**
- **Ultrahigh beam quality (high beam current, low emittance, high brightness)**





T.Tajima and J.M. Dawson PRL (1979) ***LWFA***

Advantages of LWFA in UED applications

Intrinsic synchronization between the pump laser and the probe electron beam

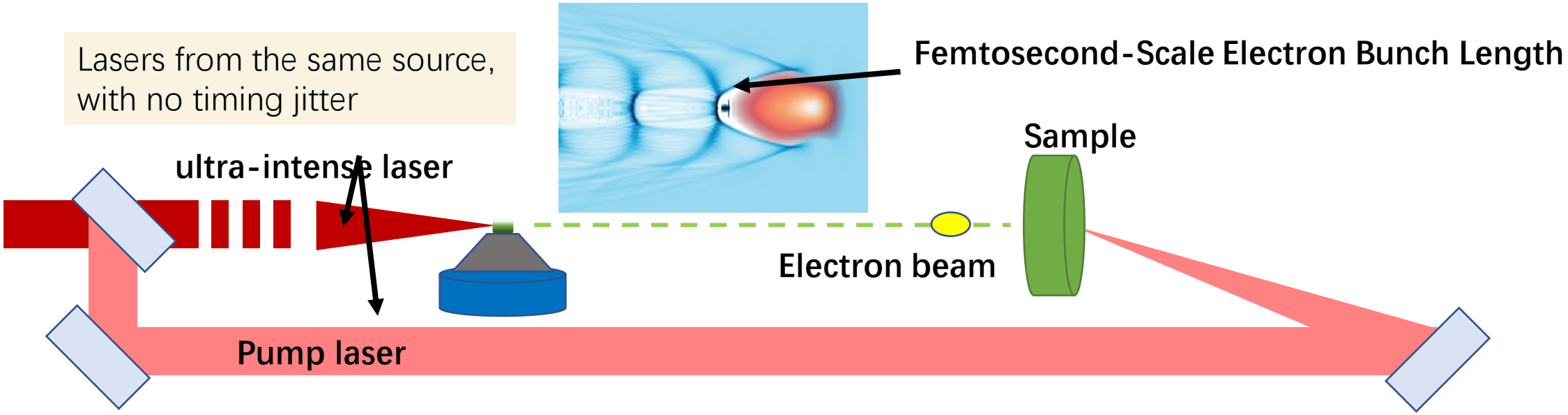
Electron source with fs-scale ultrashort initial bunch length

Potential for high-charge initial beams at the hundred-pC level

a relatively low-radiation environment

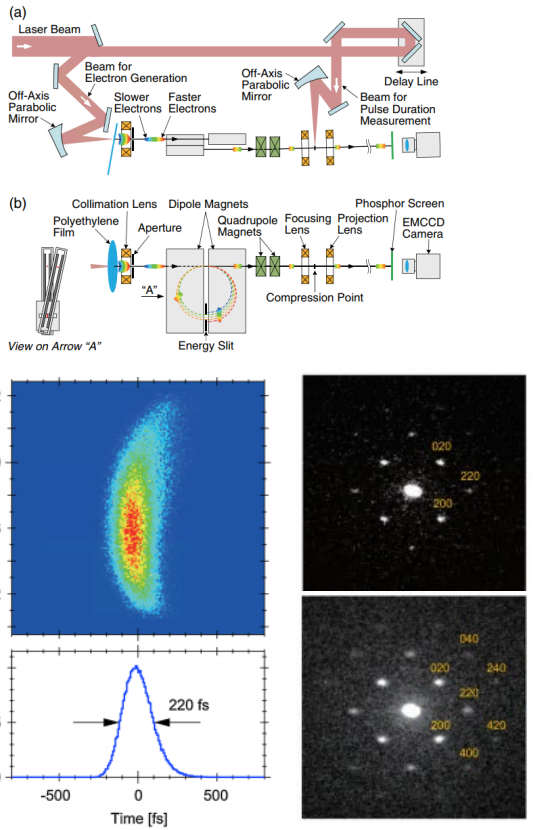
Ultrahigh temporal resolution

Lasers from the same source, with no timing jitter



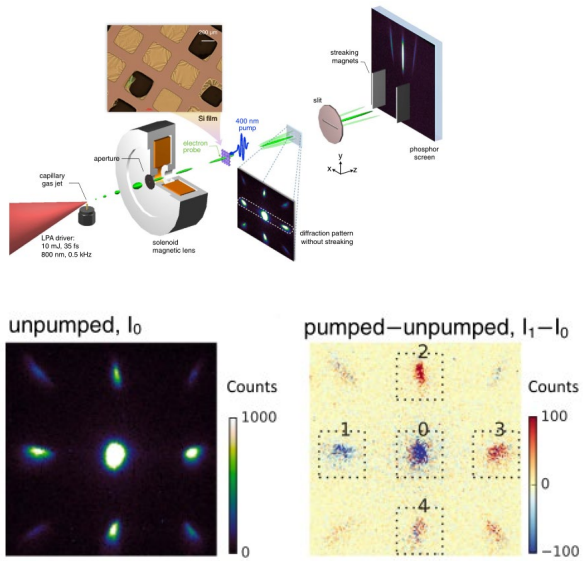
Current Status of LWFA UED

2010 350keV(1%)



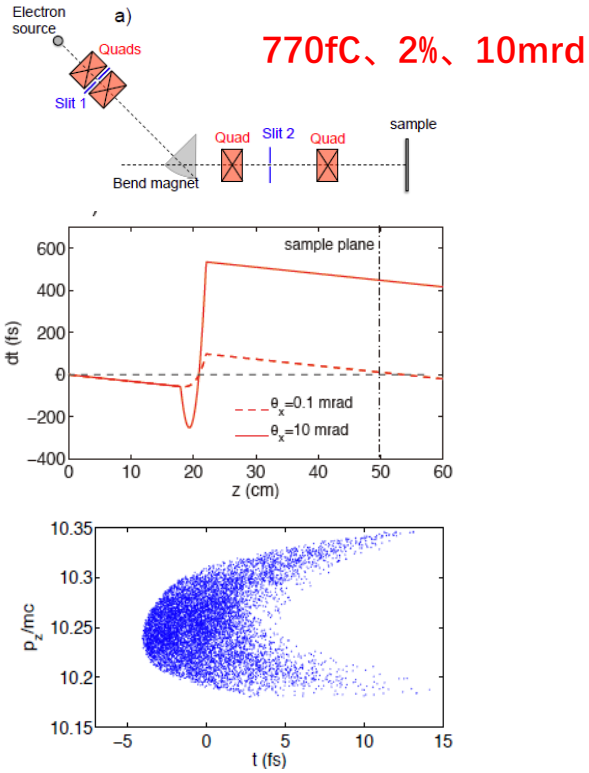
Tokita S, et al.
Phys. Rev. Lett. 105(21): 215004 (2010).

2016 95keV



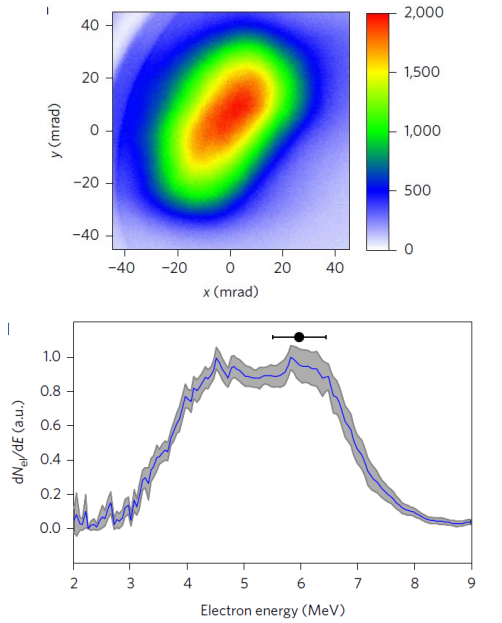
He, ZH., et al.
Sci Rep 6, 36224 (2016).

2016 5MeV (Design)



J. Faure, et al. Phys. Rev. Accel. Beams 19, 021302 (2016).

2017 5MeV electron source

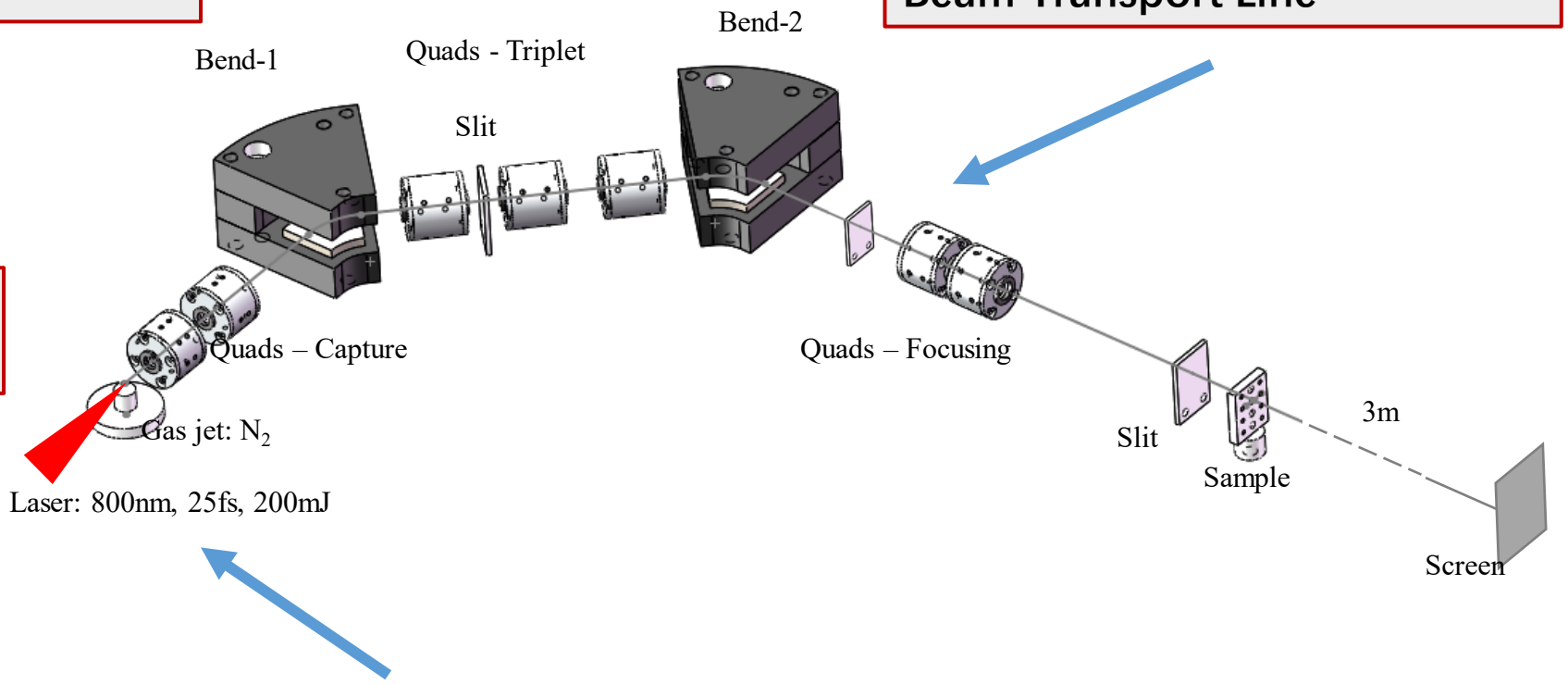


D Guénot, et al.. Nature Photonics, 11(5):293-296. (2017)

Joint Team's LWFA MeV-UED Research

How to Develop a Compact, Low-Cost MeV-UED Facility with High Temporal Resolution?

Compact Permanent-Magnet Beam Transport Line



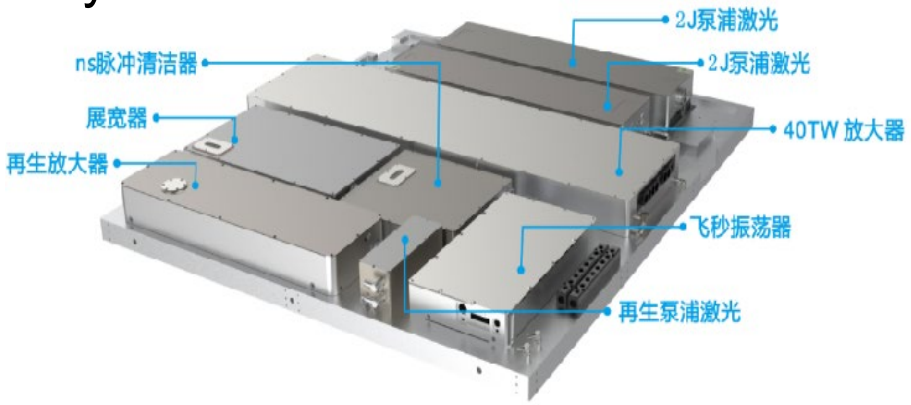
Industrial compact ultrashort, ultra-intense laser system



Laser wakefield accelerator (LWFA)

Industrial compact ultrashort, ultra-intense laser system

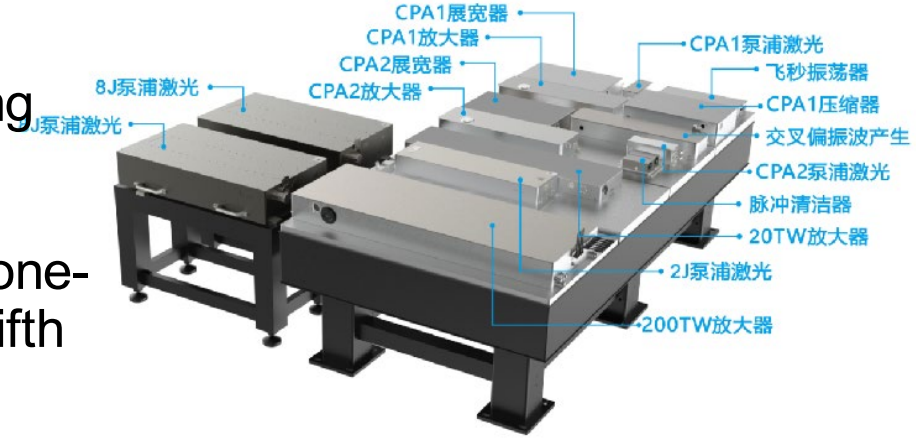
- Independent R&D of key components
- Compact
- High reliability





40TW 10Hz laser system
1.5m×1.7m

- Highly engineered system integration
- Highly modular
- Multi-dimensional parameter monitoring

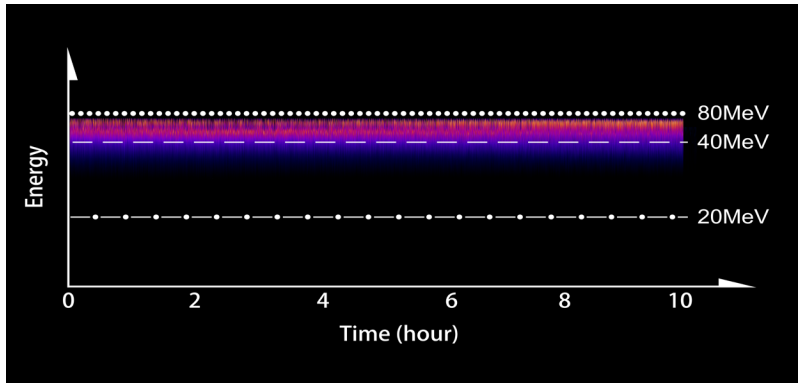


- Reduced footprint (one-third the area, one-fifth the volume)

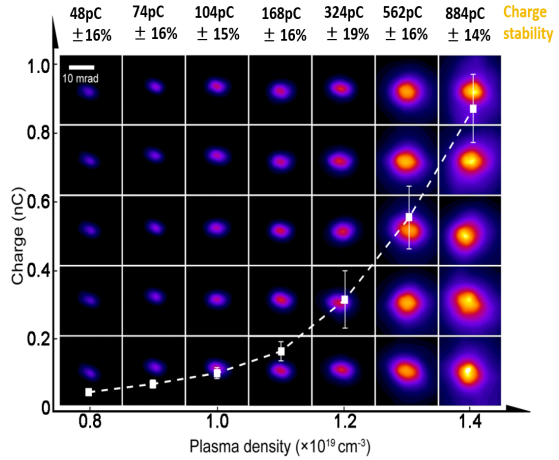


Stable Electron Beam Generation in LWFA

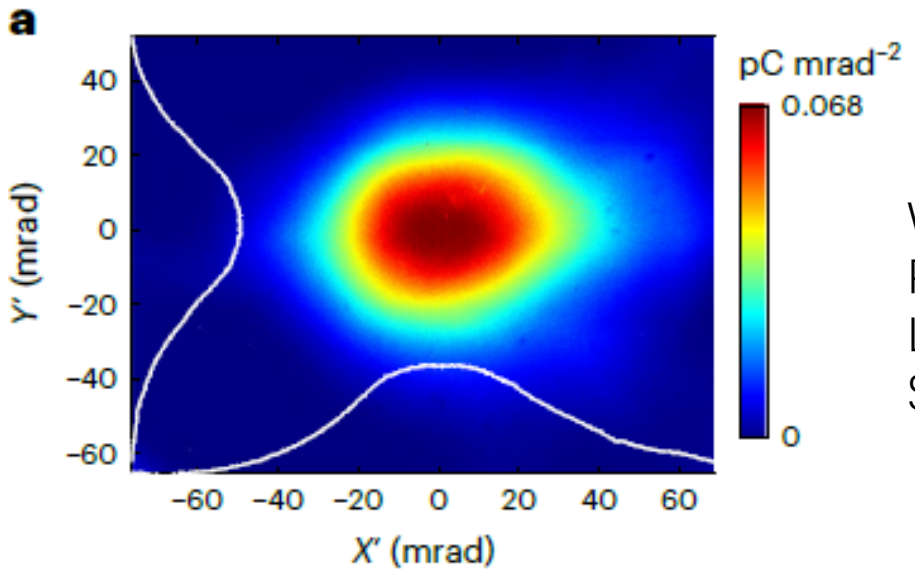
Long-term, highly stable operation



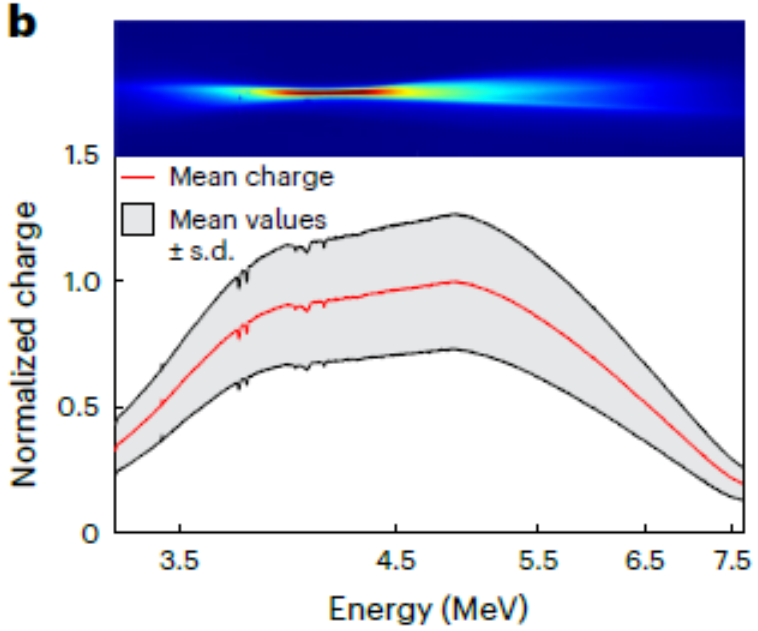
Stable high-charge beam generation



MeV electron beam generation based on a 20 TW laser system



Wavelength：800 nm
Pulse duration：24fs
Laser energy：128mJ
Spot size：6.5μm

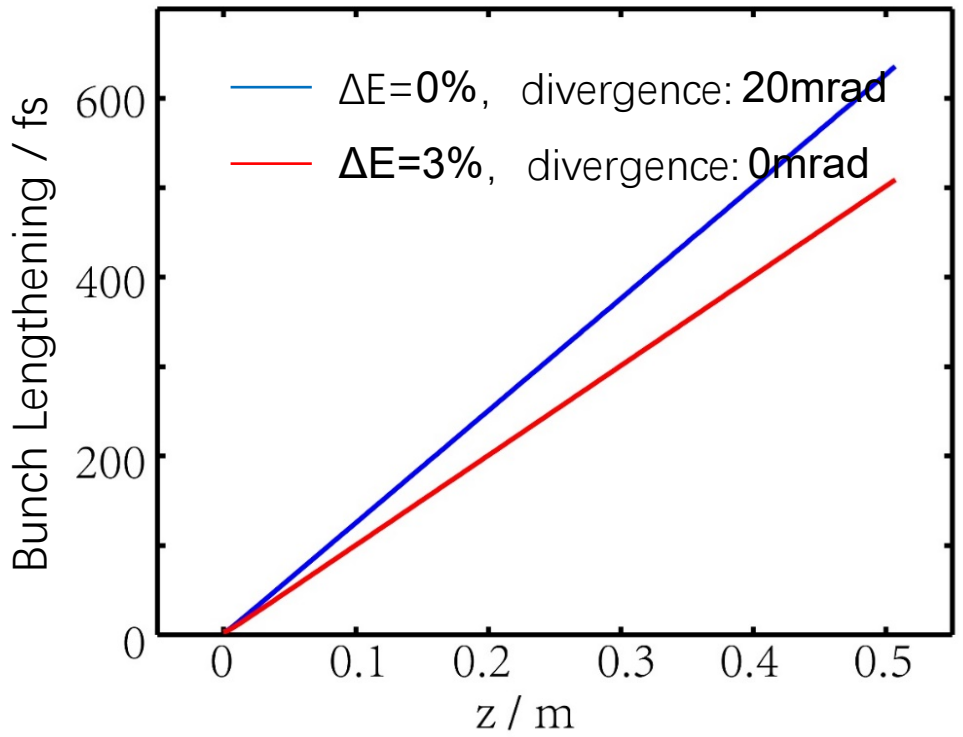


Beam Transport Scheme Design for LWFA MeV Beams

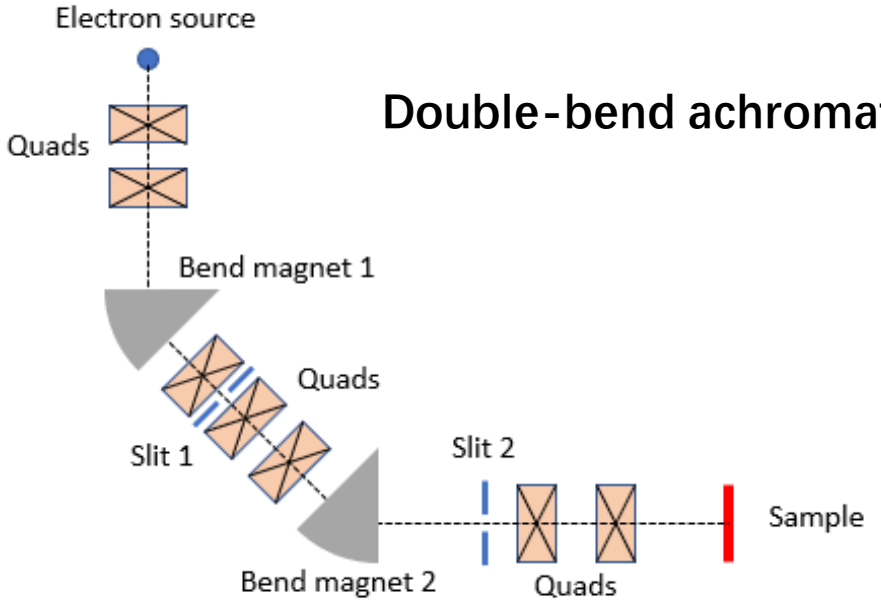
☐ Key Issues to be addressed in the beamline

Broad Energy Spectrum and Large Divergence:

- ◆ Impact on Spatial Resolution
- ◆ Severe Bunch Lengthening: Limited Temporal Resolution



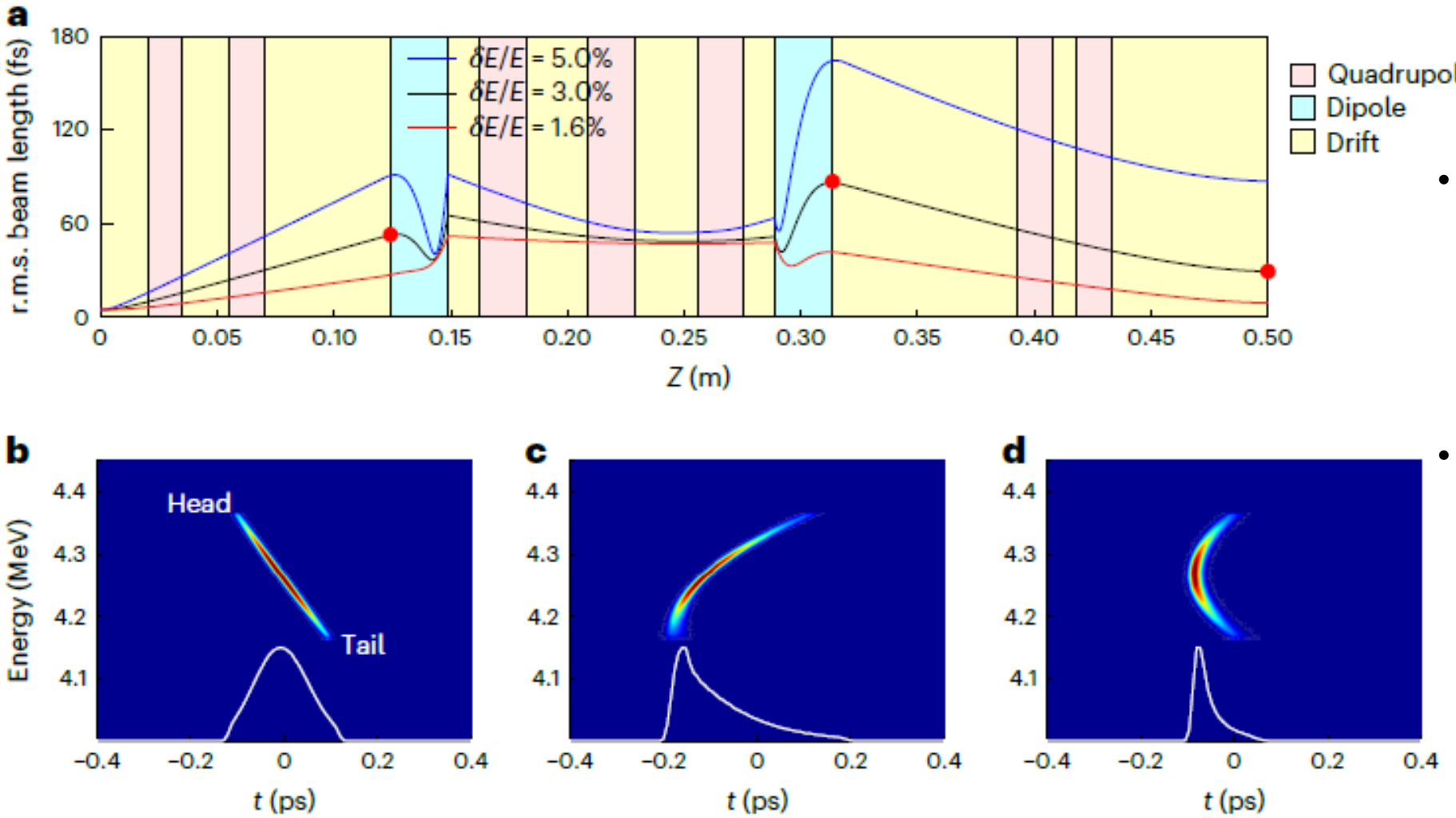
- ➢ **Energy Spread Reduction**
- ➢ **Bunch Length Compression**
- ➢ **Single-Shot Charge and signal-to-noise ratio**



Double-bend achromatic（DBA）

Research on beam dynamics simulations

Evolution trend of the bunch length and longitudinal phase space at different locations

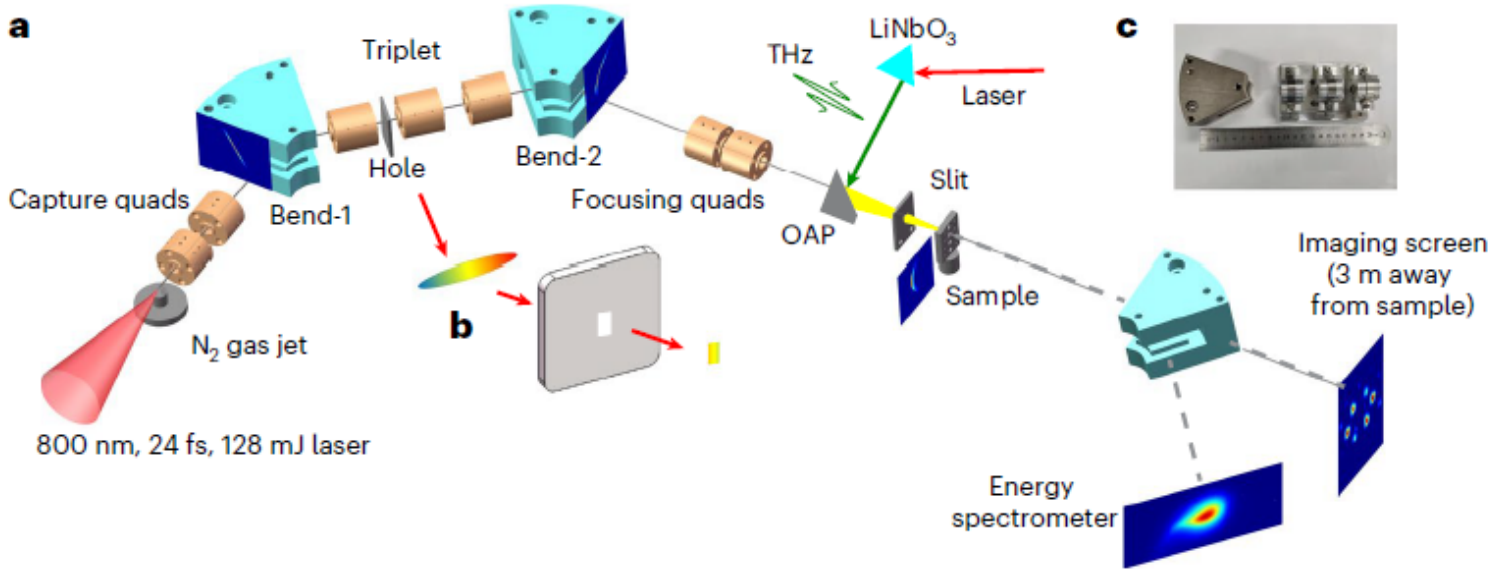


- Beam dynamics simulations demonstrate the significant effect of bunch length compression.
- Also, it indicates great potential for higher temporal resolution (fs and sub-fs).

Yu Fang, et al. Nature Photonics 20, 1056–1061 (2026)

LWFA MeV UED Platform

MeV-UED facility and experiment driven by LWFA



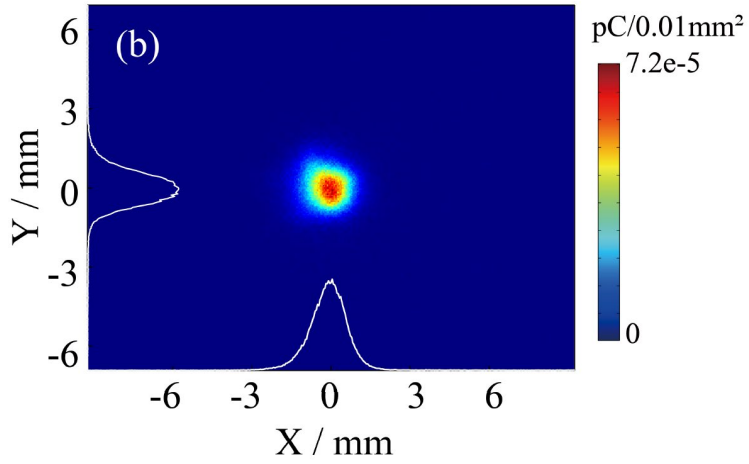
	Bend magnet	Capture quads	Quad. triplet	Focusing quads
Strength	0.434 T	63.9 Tm^{-1} 27.1 Tm^{-1}	34.0 Tm^{-1}	34.7 Tm^{-1} 27.5 Tm^{-1}
Length	28.7 mm	15 mm	20 mm	15 mm

- Compact beamline based on permanent magnets
- Electron bunch duration compression with a DBA structure
- Particle selection with slits and collimating apertures
- Longitudinal beam diagnostics with a THz deflecting cavity

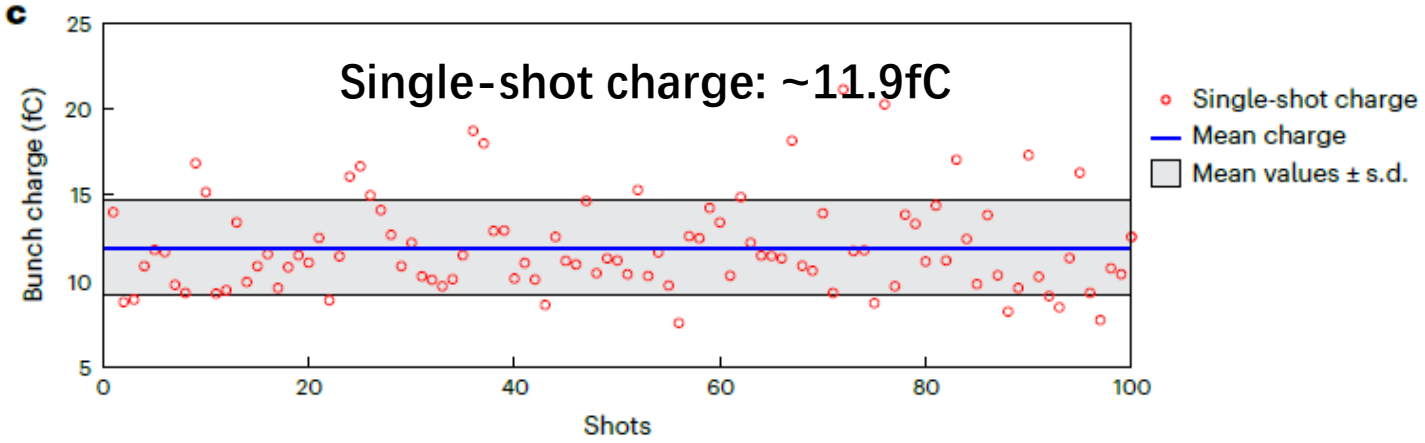
Yu Fang, et al. Nature Photonics 20, 1056–1061 (2026)

Characterization of the electron probes

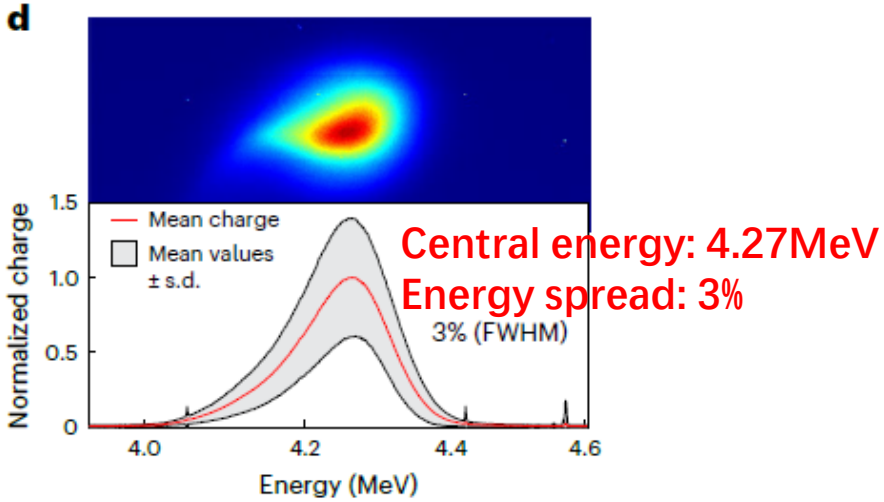
- Electron beam profile



- Bunch charge

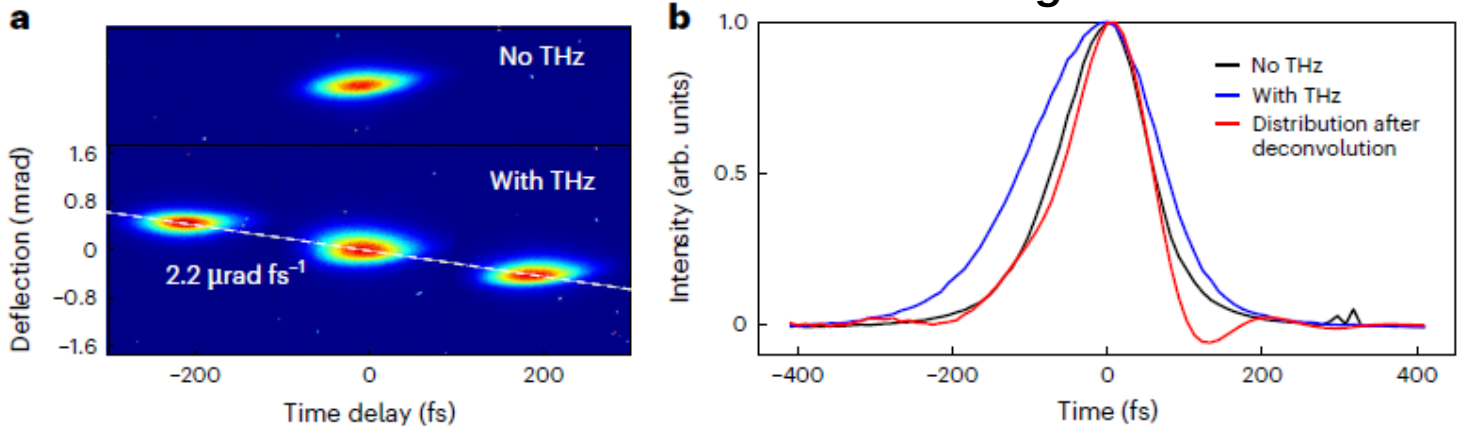


- Electron energy spectrum



Central energy: 4.27MeV
Energy spread: 3%

- Beam length



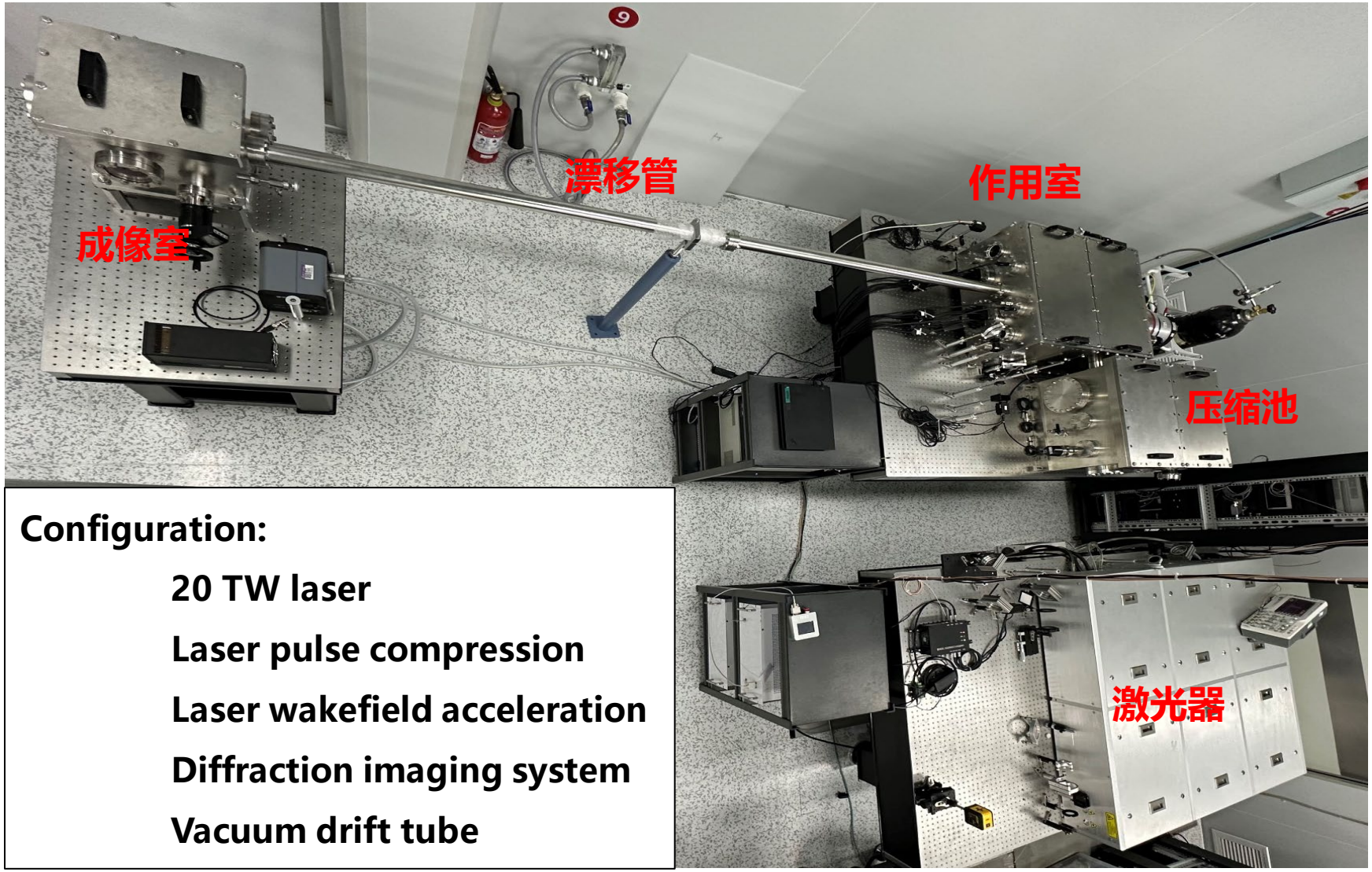
Yu Fang, et al. Nature Photonics 20, 1056–1061 (2026)

LWFA MeV UED Platform（Photograph）

- **The self-designed and constructed LWFA-driven MeV UED source**

- **Research conducted**

  - Ultrafast electron diffraction studies
  - THz-deflecting-cavity-based bunch length diagnostics
  - Diagnostics of the field profile in a THz deflecting cavity



Configuration:

20 TW laser

Laser pulse compression

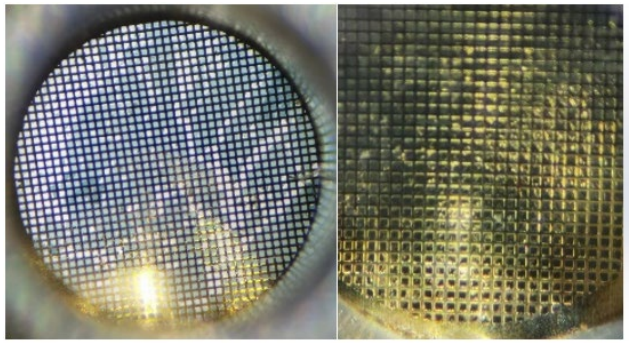
Laser wakefield acceleration

Diffraction imaging system

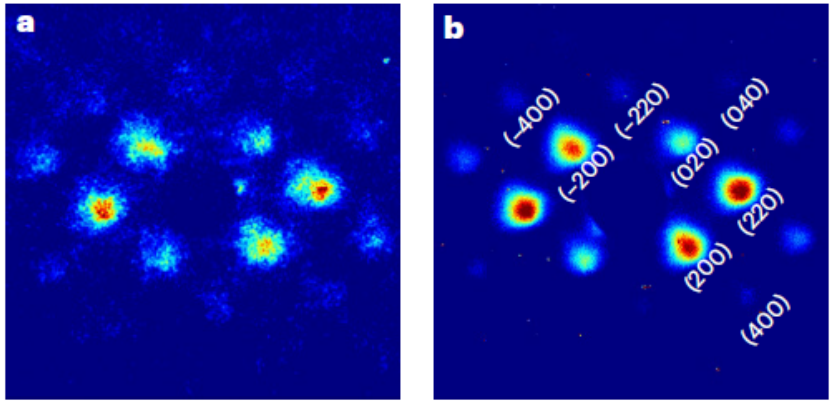
Vacuum drift tube

Electron Diffraction Verification Experiment

- Standard single-crystal gold sample: SPI, 02904-AB



- Single-crystal gold diffraction patterns



single-shot and 100-shot accumulation modes

Clearly resolved diffraction patterns:

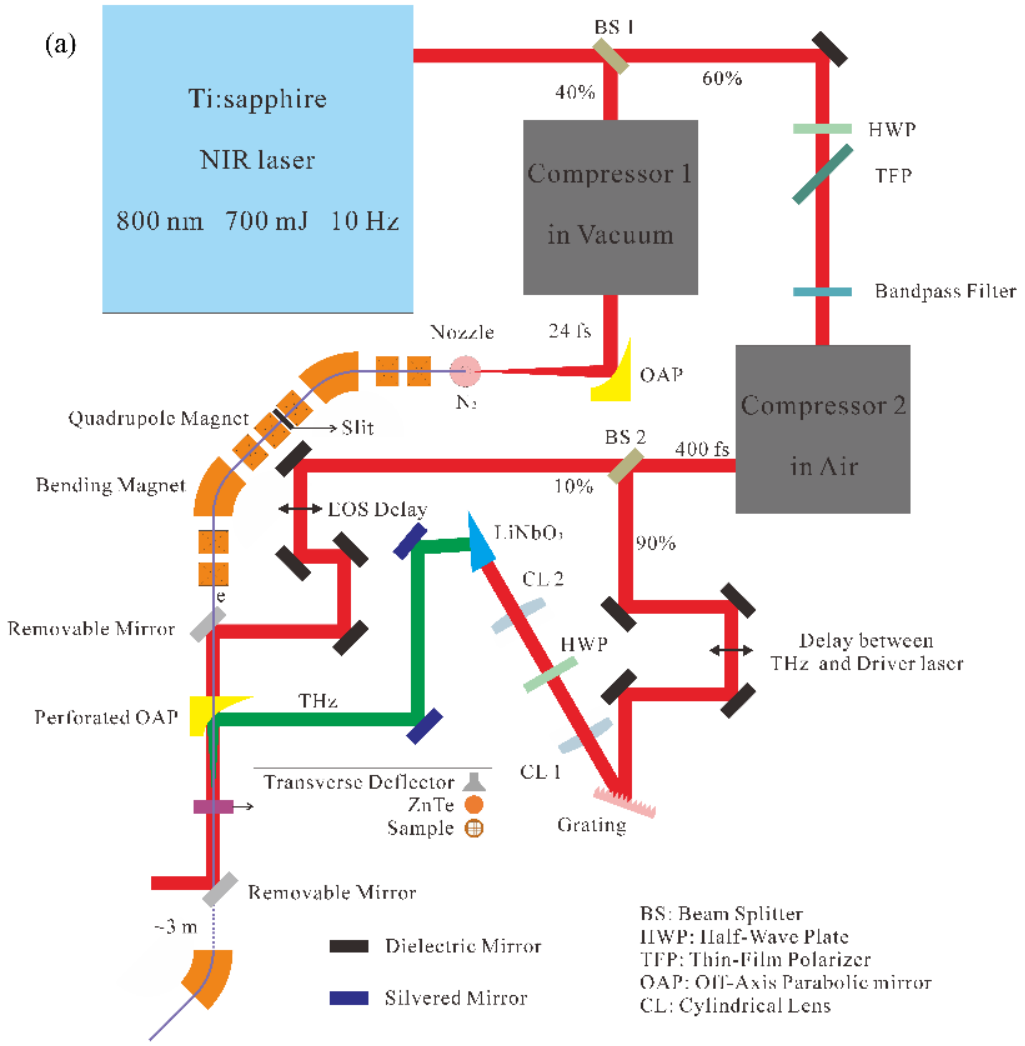
the feasibility of LWFA UED source;

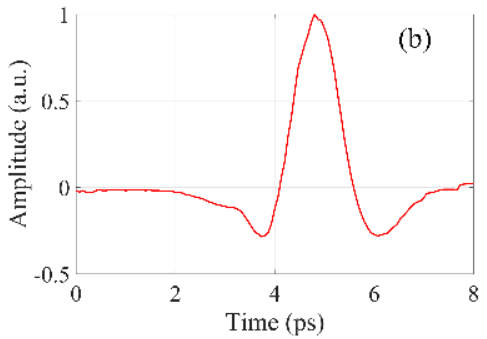
the potential of LWFA in applications

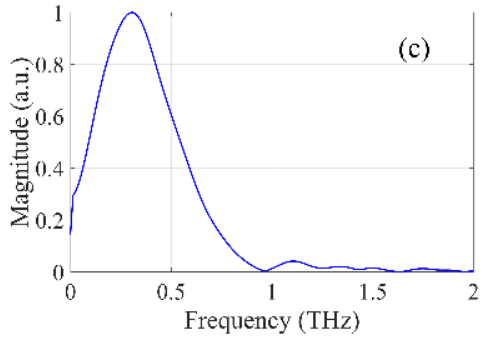
Yu Fang, et al. Nature Photonics 20, 1056–1061 (2026)

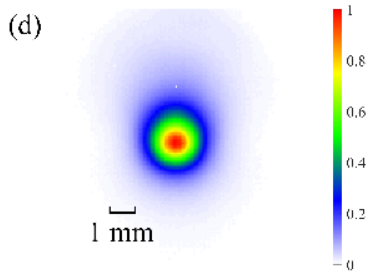
THz-Based Electron Bunch Length Diagnostics

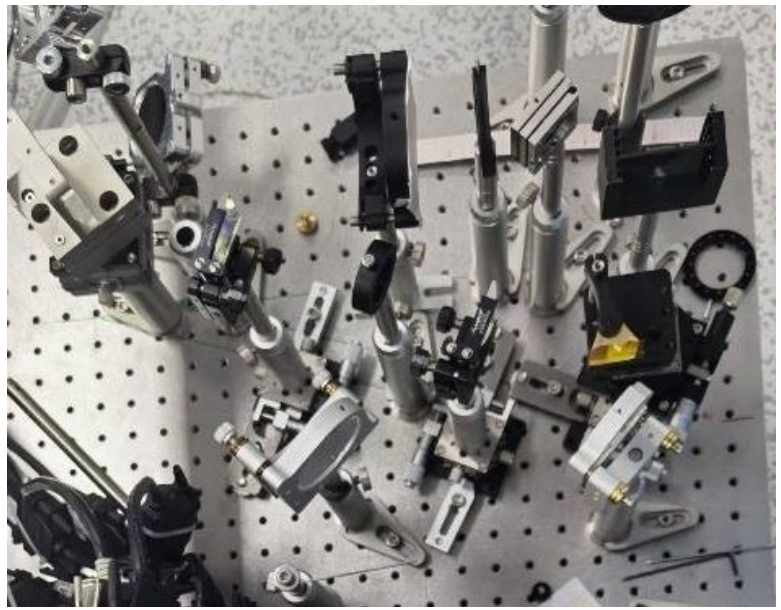
- the optical-rectification-based THz deflecting cavity setup





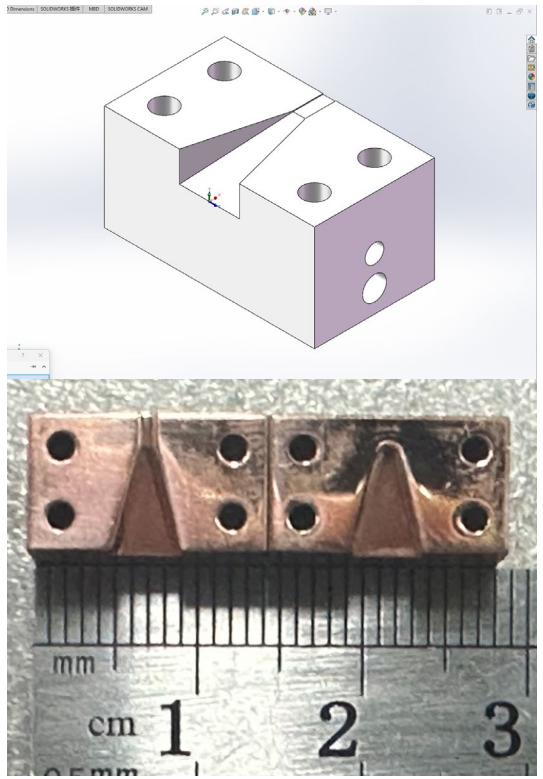




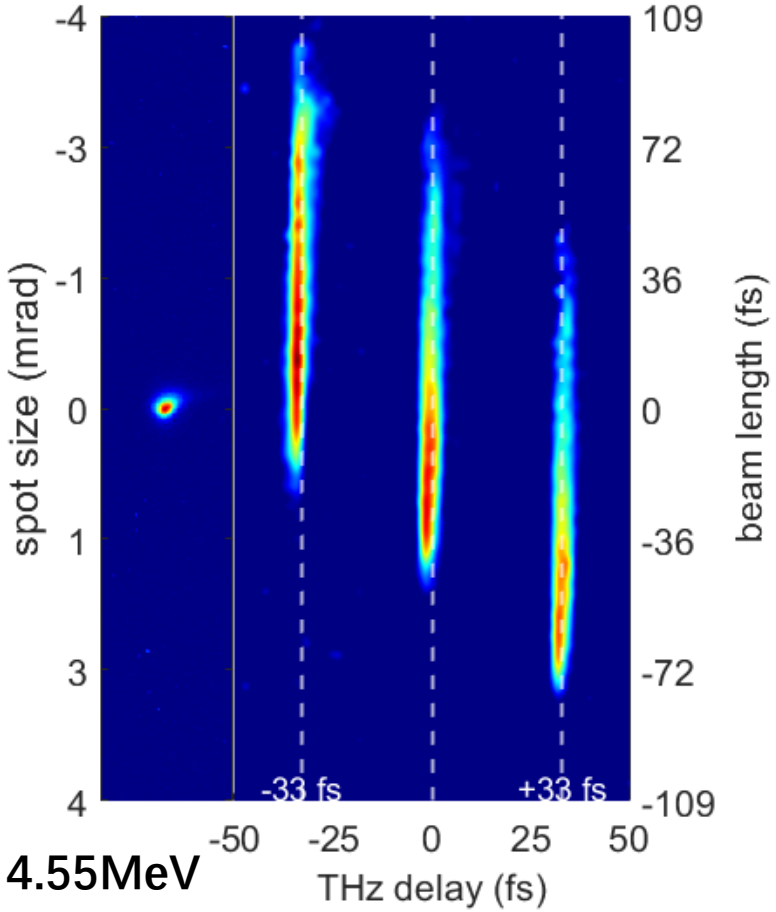


High-precision bunch-length diagnostics

Waveguide-structured THz field enhancer



Electron bunch distribution under THz deflection



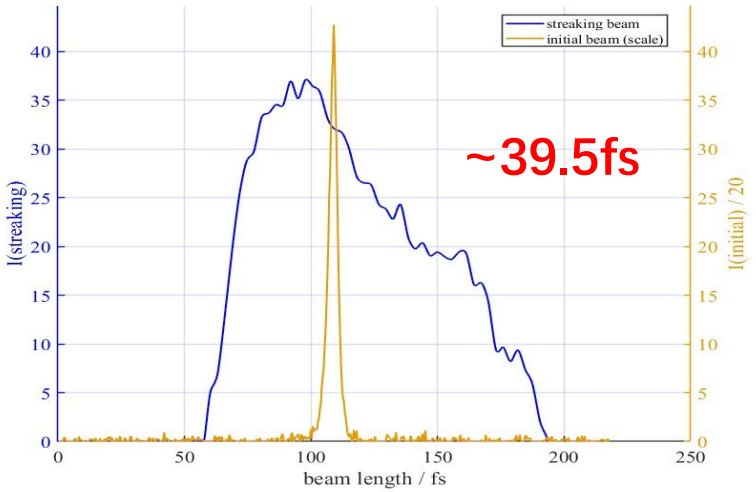
4.55MeV

Deflecting strength: ~36 μrad/fs
diagnostic precision: 1.8 fs

Experimental parameters

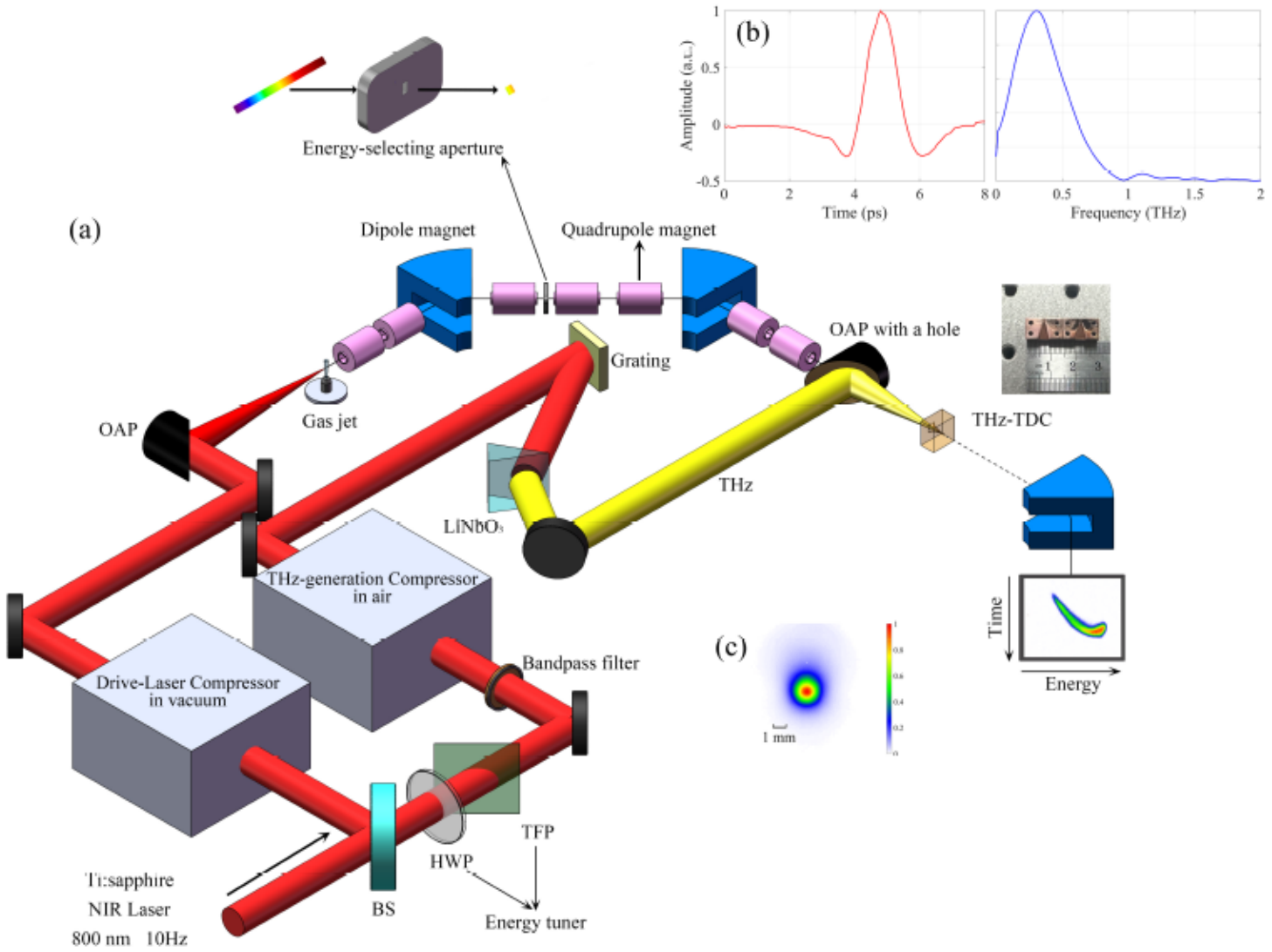
- Laser energy: ~22 mJ
- Laser bandwidth: ~15 nm
- Laser pulse duration: ~400 fs
- THz energy: ~117 μJ / 63μJ(on target)

Result of beamlength diagnostics



Longitudinal phase-space diagnostics

Setup of the longitudinal phase-space diagnostics

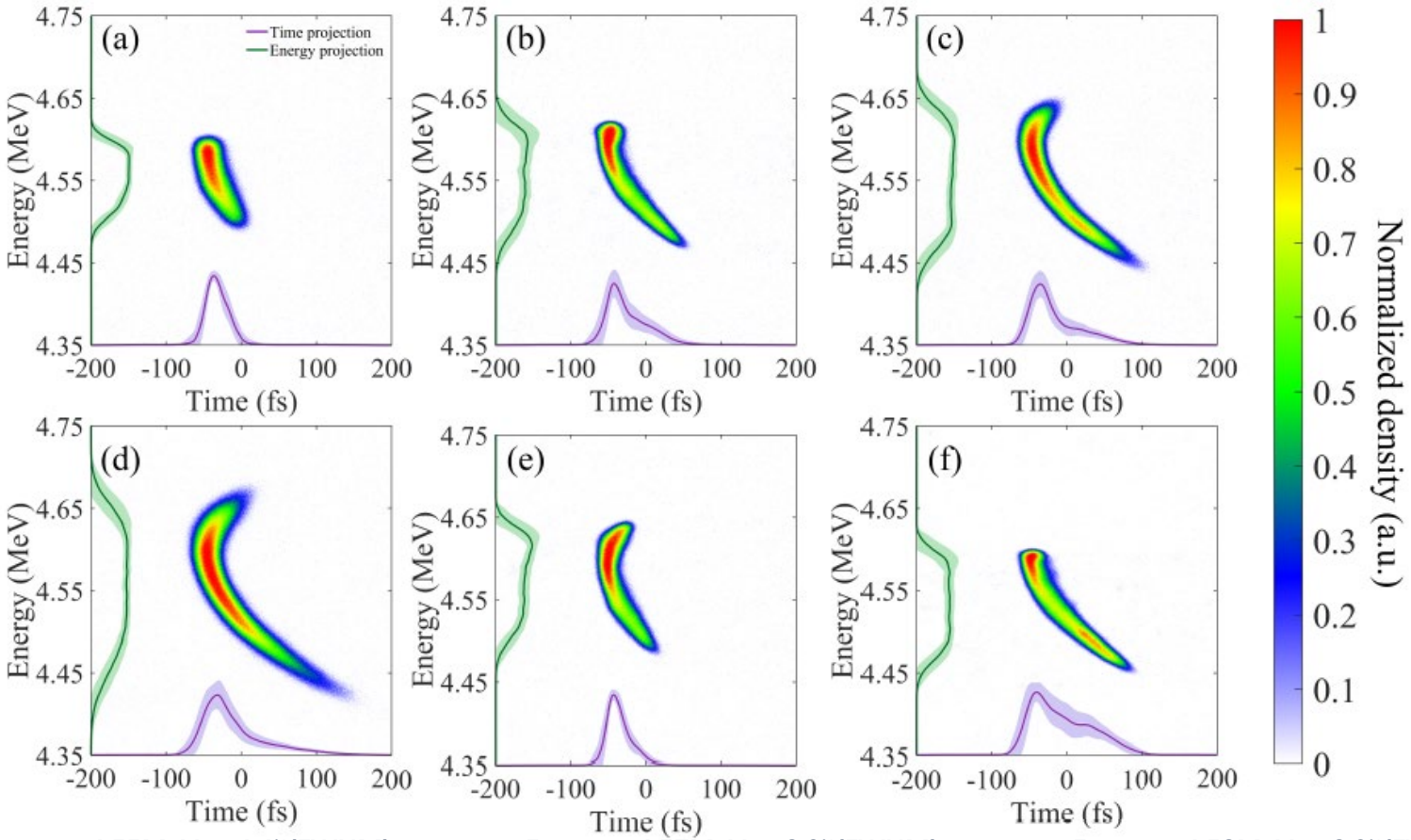


Combining a dipole magnet with bunch-length diagnostics enables beam longitudinal phase-space diagnostics.

Longitudinal phase-space diagnostics

☐ Beam dynamics validation of the isochronous structure

- Energy：4.55MeV，2%(FWHM)
- Beamlength：27 fs(rms)
- Energy：4.55MeV，2.8%(FWHM)
- Beamlength：35 fs(rms)
- Energy：4.55MeV，3.8%(FWHM)
- Beamlength：40 fs(rms)



- Energy：4.55MeV，4.4%(FWHM)
- Beamlength：44 fs(rms)
- Energy：4.57MeV，2.9%(FWHM)
- Beamlength：26 fs(rms)
- Energy：4.53MeV，2.9%(FWHM)
- Beamlength：42 fs(rms)

Variation of beam compression with central energy

(a) ~ (d)

Variation of beam compression with energy spread

(b) (e) (f)

Emergence of a trailing tail

Contribution of T_{566}

arXiv:2608.08586

THz field profile diagnostics

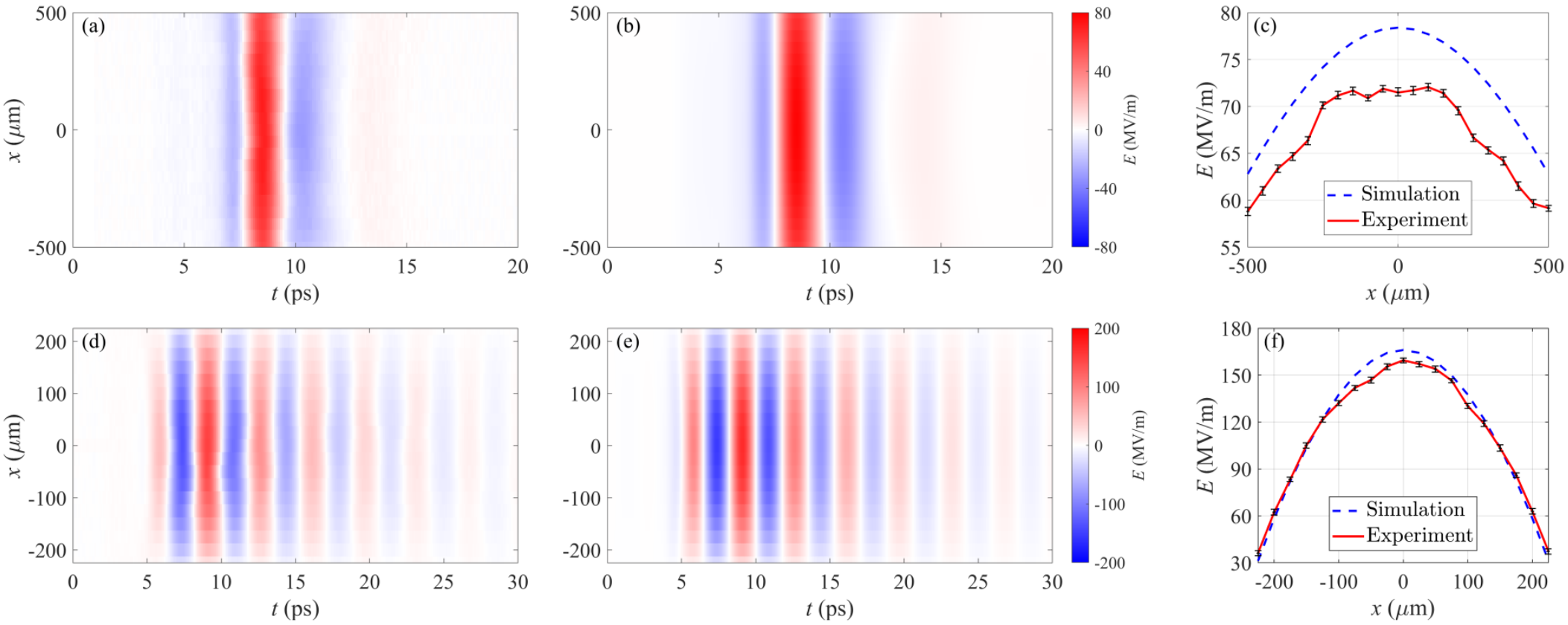
THz field profile diagnostics

Long slit

6 mm×50 μm
50 μm thick

Short slit

0.5 mm×50 μm
50 μm thick



Diagnostic results **Simulation results**

Summary

- The world's first LWFA MeV UED platform has been built, and electron diffraction validation experiments have been successfully carried out.
- A compact beam transport line based on permanent-magnet technology has been developed, enabling stable energy selection and transport of LWFA beams.
- THz-based electron bunch duration diagnostics have been completed, achieving an electron bunch length of nearly 30 fs.

- We will continue to optimize the platform performance to achieve higher temporal and spatial resolution, advance structural exploration of various materials, and strengthen interdisciplinary collaborative research.



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Thank you!

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